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SUBJECT: Significant Results Reported at the  
Apollo 11 Lunar Science Conference  
Case 340

DATE: January 30, 1970

FROM: N. W. Hinnners

ABSTRACT

The detailed reports on the Apollo 11 sample analyses were presented at the Apollo 11 Lunar Science Conference in Houston on January 5-8, 1970. Over 140 Principal Investigators covered the fields of geology, mineralogy, petrology, radiogenic isotopes, inorganic and organic chemistry, solar wind and cosmic ray spallation products, magnetic and electrical properties, physical properties, impact metamorphism and micropaleontology. The individual results, while important singly, add up to the greatest single advance in the understanding of a planetary-size body ever attained. With that in mind, I have attempted in this memorandum to integrate the salient results. Some things, such as the role of meteoroid impact in generating the regolith, the time of volcanism at Tranquillity Base and certain details of the crystallization history of the lava flows are sensibly clear. Others, including the nature of the source of the lavas, the interpretation of the old age of the regolith, and details of the solar wind-lunar surface interaction are not obvious. The clarification of problems will require much more study of the Apollo 11 samples and of new samples from Apollo 12 and future sites.

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MEMORANDUM FOR FILE

The first detailed results of the Apollo 11 lunar sample analyses were presented by the Principal Investigators in Houston on January 5-8, 1970. In this memorandum I have attempted to integrate the salient results of ~140 papers presented there. The reader should keep in mind the fact that there has not yet been any critical review of the papers presented. Where numbers are mentioned, they should be taken only as representative since overlap of investigations and inhomogeneous samples results in variation. Because of the great overlap and the sheer number of papers, it is impractical to attribute each piece of information to a given Investigator. The interested reader is referred to the upcoming January 30 issue of "Science" for the individual papers.

Sample Locale

The lunar samples returned on Apollo 11 from Tranquility Base were collected from a cratered mare surface about 40km from the nearest surface highlands. The samples came from the uppermost part of a fragmental debris layer, called the regolith, which ranges from 3 to 6m (~4m mean) in thickness near the LM landing spot. By far, the major component of the regolith and representing one type of returned sample, is the weakly cohesive fine-grained matrix (<1cm by definition) consisting of material ranging from small rock chips to microscopically small rock fragments, glass particles, and meteorite debris. Mixed in with and lying on top of the fines are pieces of "rock" ranging in size from small chips to ~1m boulders. Three rock types were returned:

1. basalts: fine-grained (~0.05-0.2mm) vesicular crystalline igneous rocks;
2. micro-gabbros: medium-grained (~0.2-3.0mm) "vuggy" crystalline igneous rocks; and
3. breccia: an indurated physical mixture of the fines and fragments of the rock types.

A notable aspect of the rocks is the extensive millimeter to submillimeter pitting and microfracturing of the surfaces caused by long exposure to meteoroid bombardment. Further manifestation of the impacts is the occurrence of glass, commonly as a lining of the smaller pits or craters and occasionally as a spatter crust on the rock surfaces. The correlation of crater density with roundness of rocks and occurrence of craters on all sides of rocks indicates the effectiveness of meteoroids in eroding and turning over or gardening the lunar surface.

A word of caution is necessary before proceeding to a discussion of the crystalline rocks: the minor or non-existent shock effects in most crystalline rocks and the nearness to the LM (~50m) of ejecta from West Crater (~400m away) lead one to conclude that most rocks originated in the nearby mare but it cannot be unequivocally demonstrated.

#### Origin of Crystalline Rocks

Both the fine-grained (basaltic) and medium-grained (micro-gabbroic) rocks can be demonstrated to have crystallized from igneous melts over a temperature interval of ~1075°-1225°C. This temperature range, based upon oxygen isotope geothermometry and observations of the melting ranges of the rocks, is similar to that observed for terrestrial basalts. Primarily because of the relatively low Si and Al, however, the lavas were an order of magnitude less viscous than the usual terrestrial basalts, possibly explaining the great expanses of lunar mare apparently covered by individual flow units.

Both crystalline rock types contain the same major minerals:

1. 45-55% clinopyroxene of a type called pigeonitic or subcalcic augite. A crude average composition is  $\sim(\text{Ca}_{.3}\text{Fe}_{.3}\text{Mg}_{.4})\text{SiO}_3$ . Extreme zoning within grains and grain-to-grain variations account for the wide range of compositions reported:  $(\text{Ca}_{.25-.4}\text{Fe}_{.17-.70}\text{Mg}_{.05-.43})\text{SiO}_3$ . The clinopyroxene is often an intimate mixture of two clinopyroxene phases — augite (relatively richer in Ca) and pigeonite (relatively richer in Fe and Mg), with the pigeonite evidently having been exsolved from an initially homogeneous high temperature phase. There are significant amounts of Cr, Ti, and Al and other "impurities" in the clinopyroxene structures.

2. 25-35% plagioclase feldspar, a solid solution series of two end-members represented by albite ( $\text{Ab} = \text{NaAlSi}_3\text{O}_8$ ) and anorthite ( $\text{An} = \text{CaAl}_2\text{Si}_2\text{O}_8$ ). The lunar plagioclase is rich in the An component, an average being  $\sim\text{An}_{80-90}$  with grain-to-grain variation and crystal zoning accounting for a range of  $\sim\text{An}_{60-98+}$ . The plagioclase usually contain significant amounts of iron ( $\sim 0.3\%$ ) and titanium ( $\sim 0.1\%$ ) and lesser amounts of other "impurities."
3. 10-20% ilmenite -  $\text{FeTiO}_3$ . The Fe and Ti are roughly stoichiometric except for occasional major amounts of Cr and Zr. Ilmenite frequently shows exsolution needles of rutile ( $\text{TiO}_2$ ) and exsolution lamellae of ulvöspinel ( $\text{Fe}_2\text{TiO}_4$ ).

Minor amounts of the following minerals have been found:

1. Olivine (0-5%) - a solid solution series in which forsterite ( $\text{Fo} = \text{Mg}_2\text{SiO}_4$ ) and fayalite ( $\text{Fa} = \text{Fe}_2\text{SiO}_4$ ) are the end members. The lunar olivine has a composition of  $\sim\text{Fo}_{55-70}$ . Relative to terrestrial olivine, trace Ni is low, Cr high.
2. Cristobalite, Tridymite, Quartz - up to a few %. All are polymorphs of  $\text{SiO}_2$  with cristobalite being stable at high ( $>1473^\circ\text{C}$ ), tridymite at intermediate ( $870^\circ\text{C}$ - $1473^\circ\text{C}$ ) and quartz at low, ( $<870^\circ\text{C}$ ) temperatures.
3. Troilite -  $\text{FeS}$  with traces of Ni, Ti, and Cr.
4. Native iron (kamacite) - Fe (with low Ni).
5. Apatite (traces only) -  $\text{Ca}_5(\text{F, Cl})\text{P}_3\text{O}_{12}$  with minor Si and Fe.
6. Ulvöspinel (traces) -  $\text{Fe}_2\text{TiO}_4$  - as occasional discrete grains and as exsolution lamellae in ilmenite.
7. Orthoclase (potassium feldspar) -  $\text{KAlSi}_3\text{O}_8$  - minor amounts.

8. Rutile -  $\text{TiO}_2$  - as exsolution needles in ilmenite.
9. Zircon -  $\text{ZrSiO}_4$  - rare.
10. Beddeleyite -  $\text{ZrO}_2$  - rare.
11. Native copper - rare.

Four new minerals or mineral varieties have been identified:

1. An iron-rich "pyroxenoid" of composition  $\sim(\text{Fe}_{.85}\text{Ca}_{.13}\text{Mg}_{.02})\text{SiO}_3$  [compare chemically with clinopyroxenes].
2. An iron-titanium-chromium spinel  $\sim\text{Fe}_{1.0}(\text{Cr}_{.7}\text{Ti}_{.6}\text{Fe}_{.37}\text{Al}_{.33}\text{Mg}_{.23})\text{O}_4$ .
3. Magnesian ferropseudobrookite - essentially  $\text{Fe}_{.5}\text{Mg}_{.5}\text{Ti}_2\text{O}_5$ .
4. An iron-titanium-zirconium silicate.

The question now is, what does all the above tell us? First, the major mineral types are common constituents of terrestrial basalts but the clinopyroxene-feldspar ratio is larger and the relative amount of ilmenite is exceptionally high in the lunar rocks. The high clinopyroxene may represent high clinopyroxene in the source material or (see below) there may have been removal of plagioclase from the initial melt. Whether the source region of the rocks contained large amounts of ilmenite or whether the particular rocks represent part of a layered structure in which ilmenite was gravitationally concentrated is unknown. The most iron-rich lunar pyroxene zones are not found in terrestrial rocks. Their occurrence in the Apollo 11 samples and the relatively large amount of iron in the plagioclase is indicative both of the moderately high iron content of the magma and progressive enrichment of iron (and  $\text{SiO}_2$ ) in the melt as crystallization progressed (see below).

Likewise the large amount of titanium in the clinopyroxenes and feldspars is attributable to initially high titanium content.

The plagioclase is more calcic than the usual terrestrial basaltic plagioclase, indicative of a low abundance of sodium in the rocks and probably in the source material.

The occurrence of native iron and the absence of ferric ( $\text{Fe}^{+++}$ ) iron reflect the low partial pressure of oxygen — estimated to be  $\sim 10^{-13}$  bars at  $1200^\circ\text{C}$ , at least three to four orders

of magnitude less than that of terrestrial basalts. The resulting (non-earth-like) high initial concentration of ferrous iron ( $\text{Fe}^{++}$ ), the progressive enrichment of the melt in iron as crystallization proceeded, plus the relatively large amounts of chromium, titanium, and zirconium accounts for the occurrence of the new minerals.

The apatite is unusual in that there is no water in the fluorine and chlorine sites, possibly reflecting low water in the melt.

The  $\text{SiO}_2$  polymorphs are common in terrestrial igneous rocks and represent part of the last material to crystallize from the melt. The cristobalite and tridymite are metastable. Their survival is indicative of rapid cooling, relative to typical "deep-seated" rocks, and low water content. The rapid cooling interpretation is supported by the small grain size and detailed analysis of crystal growth patterns. In summary, all signs are consistent with an interpretation that the crystalline rocks were part of a surface lava flow(s).

The virtual absence of water (at the 100ppm level) is manifest in two ways. First, there are no signs of mineral hydration so common in terrestrial rocks. Second, the oxygen isotope geothermometry for the micro-gabbros indicates the same high temperature as do the basalts whereas terrestrially isotopic exchange between the minerals and water in gabbroic rocks commonly occurs to lower temperatures. These observations, plus the evidence for rapid cooling of the basalts (favoring hydration) lead me to conclude that there never was any water in the rock melt (as distinguished from water boil-off during lava extrusion).

The crystalline rocks seem to have started and finished crystallizing from a mass of melt not much greater than that of the final rock. This is evidenced by the grain-to-grain chemical heterogeneity and by extensive zoning of individual clinopyroxene crystals which have calcium and magnesium-rich interiors and iron-rich rims. Similarly plagioclase feldspar crystals frequently show a zoning outwards as calcium decreases relative to sodium.

Many investigators assume that the difference in grain size which initially distinguished basalts from micro-gabbros simply reflects a difference in cooling rate, the coarser micro-gabbros arising from a more slowly cooling interior of a flow

unit. If life were that simple, the chemistry of the rocks should be simply related. In fact, it appears that although the rocks are similar for several major elements (e.g., Si, Ca, Mg, Al, O) the two rock types differ sufficiently with regard to U, Th, K, Rb, Cs and Ba, (the basalts usually contain more than the micro-gabbros) such that it takes addition of a third component to the micro-gabbroic rocks in order to derive the basalts.

Both crystalline rock types are abnormally high in refractory elements, e.g., Ti, Zr, Hf, Y, and the rare earths, but low in volatiles, e.g., Bi, Hg, Cu, Zn, Cd, Tl, Pb, Ge, Cl, Br, As, and Sb relative to assumed solar abundances (on an H and He-free basis). Although it is risky to speculate on the cosmic significance of the above, it is difficult not to believe that the bulk of the lunar material has had a high temperature history at some point, presumably during its origin. The lunar K/U of  $\sim 3000$  (earth  $\sim 10,000$ ), a ratio not expected to change during igneous differentiation, supports such an interpretation as does data (see below) indicating that the lunar rocks "grew" in a Rb/Sr environment much lower than that of the earth or chondritic meteorites.

It was pointed out by many that the crystalline rocks most closely resemble oceanic ridge basalts or certain types of meteorites. These analogies are interesting, but since there is no 1:1 equivalence, comparisons result in exercises of speculation.

An interesting aspect of the crystallines is that the troilite evidently separated as an immiscible sulfide liquid late in the solidification sequence. Likewise, when the rocks were 90-98% crystallized, the residual silicate liquid separated into two immiscible phases, now mostly glasses, with one phase being high in equivalent orthoclase (potash) feldspar and silica content - not unlike "granite" in composition. Whether or not significant amounts of such "granite" exist on the moon remains to be seen, but it is established to be possible.

A key question is, does the rock represent a sample of the unaltered lunar interior, is it a result of partial melting, or a result of fractional crystallization? High pressure experiments indicate that the basalts ( $\rho \sim 3.2$  g/cc) invert to a high density ( $\rho \sim 3.6$  g/cc) garnet-bearing assemblage called eclogite at  $\sim 12$  Kb (equivalent to  $\sim 350$  km) at  $1100^\circ\text{C}$  (or  $\sim 0$  Kb at  $500^\circ\text{C}$ ). Such a dense rock is not compatible with the lunar moment of inertia/ $MR^2$  value of  $\sim 0.402 \pm 0.002$ . Considering the second alternative, it may be possible to derive the observed rocks by the partial melting ( $\sim 3\%$ ) of an interior composed predominantly of

pyroxene but such an explanation is purely hypothetical at this point since no evidence for such a rock exists. The last mentioned alternative of fractional crystallization was favored by many attendees for the following reason: the rare earth elements (REE) exhibit an unusual (3X to 4X) depletion in europium. Europium is unique among the REE in that under highly reducing conditions such as exhibited by the lunar rocks, it can also exist in the +2 valence state while the others are in the +3 state. As such, europium preferentially concentrates in the calcic plagioclase feldspar relative to pyroxene and ilmenite, a fact born out by the analysis of REE in separated mineral phases. One could account for the missing europium by hypothesizing that crystallization of large masses of almost pure plagioclase feldspar preceded extrusion of the basaltic rock liquids. Such masses of feldspar (referred to as anorthosite) should exist, possibly constituting the highlands and/or sub-mare regions. This hypothesis would be no more than speculation either except (see below) that fragments of anorthosite and anorthositic gabbro rock and glass have been found in the soil, such fragments presumably having been blasted in from the highlands or sub-mare regions by meteoroid impacts. Supporting a highlands source interpretation is the rather good fit between the anorthosite chemistry and Surveyor VII results at Tycho.

#### Origin of Soil and Breccia

As demonstrated by bulk chemistry and mineralogic studies, the soil at Tranquillity is for the most part a comminuted, sometimes melted, mixture of the two crystalline rock types while the breccia (see below) appears to be a physically indurated equivalent of the soil. In detail, however, it is obvious that soil and breccia contain components other than the crystalline rocks. For example, the total soil has less ilmenite than the rocks, indicative of dilution by a low ilmenite rock (it was also noted that the meteoroid gardening might lead to a gravitational concentration of ilmenite in the lower regolith - below the sampled ~10cm).

The nickel content of the fines (~190ppm) as compared to that of the crystalline rocks (<20ppm) is indirect evidence for a meteorite component of the fines. Direct evidence is available in the form of iron-nickel particles in the glasses of the fines and in the observation of actual fragments of meteoritic cohenite ( $\text{Fe}_3\text{C}$ ) and schreibersite  $(\text{Fe,Ni})_3\text{P}$ . The elements C, Ir, Pd, Au, Ag, Zn, Cd, Br, Bi, and Tl are 2-100 times more abundant in the fines and breccias than

in the crystallines. While, potentially, solar wind carbon could account for the carbon anomaly, it takes addition of 1-2% of carbonaceous chondrite meteorite debris to the fines and breccias to account for most of the other anomalies. (Note that there is still too much Zn and Cd in the soil and breccia.) Arguments based upon abundances of Re, Os, Ir, and Au indicate that iron meteorites per se contribute <<1% to the soil.

In addition to the apparent carbonaceous chondrite meteorite content, the soil contains (~0.5%) fragments of rocks composed almost entirely of calcium-rich plagioclase feldspar ( $\text{An}_{90+}$ ). These same rocks, anorthosites and anorthositic gabbros are represented chemically by the relatively minor amount (~0.1%) of almost colorless glass.

Shock effects are amply visible in both the crystalline fragments and glasses of the soil and breccia. These effects are manifest by fracturing, creation of planar features (including glass lamellae), partial fusion to complete fusion of minerals, and the formation of glass (solid state transformation to glass). Correlation of observed effects with terrestrial analogues indicates peak shock pressures of 100-200Kb in both the soil and breccias. Evidently the breccia has been produced by shock lithification of the soil at pressures about the same as those producing the soil itself. An alternative explanation given was that the breccias were produced by a welding process in a "hot" base surge associated with a relatively large impact event. Regardless of which is correct (there's really no reason why both can't be) there is evidence in the form of impact pits (the so-called zap craters) and agglomerations of small iron and glass particles on larger fragments that there is mutual impact among hot particles in the ejecta cloud or ray during an impact event.

In addition to the elemental chemical differences between soil and crystalline rocks, it is clear that the soil is enriched in the heavier isotopes of sulfur ( $\text{S}^{34}$  vs.  $\text{S}^{32}$ ), silicon ( $\text{Si}^{30}$  vs.  $\text{Si}^{28}$ ), oxygen ( $\text{O}^{18}$  vs.  $\text{O}^{16}$ ), and carbon ( $\text{C}^{13}$  vs.  $\text{C}^{12}$ ). A possible explanation is selective loss of lighter Si and O during impact vaporization of  $\text{SiO}_2$  and selective loss of lighter  $\text{H}_2\text{S}$  and  $\text{CH}_4$  (where the H comes from solar wind).

Of particular interest is the water and hydrogen content of the soil and breccia and its deuterium content. The concentration ran as high as ~800ppm  $\text{H}_2\text{O}$  in soil and to ~450ppm in the breccia with deuterium ranging from 20-70ppm of the hydrogen

in the water. The measured deuterium in the hydrogen gas (presumed to be of solar wind origin) is from 5-30ppm of the hydrogen but this may reflect isotopic equilibration of hydrogen with the water since solar wind hydrogen should theoretically contain much smaller amounts of deuterium. The low deuterium, relative to terrestrial water ( $\sim 150$ ppm deuterium in hydrogen), and thermal release patterns rule against contamination as a source of the lunar water and indicate that the earth has lost  $\sim 2/3$ 's of its initial hydrogen if it had "lunar" water to start with.

### Age Determinations

Perhaps one of the most significant aspects of the Conference concerns the radiometric ages obtained for various samples. Consider that before Apollo 11 the only way to get an estimate of the absolute age of the lunar surfaces was to ascertain the crater density at some particular size(s), assume that the craters were produced by meteoroid impact, estimate the current meteoroid flux creating that size crater, assume constancy of flux with time, and divide density by production rate. Such techniques yielded estimates ranging from  $\sim 1/2$  to 4 billion years. The return of the samples opened the door to radiometric age dating in which one estimates "age" by determining the amount of daughter isotope produced by a radioactive parent of known half-life. The common techniques used for Apollo 11 samples relied on methods utilizing certain isotopes of rubidium (Rb), potassium (K), uranium (U), and thorium (Th) as the radioactive parents. Since most age determinations are done on a routine basis by determining only the elemental abundance of Rb, K, U, and Th, it was necessary to establish that the relative isotopic abundances of lunar Rb, K, U, and Th were the same as terrestrial abundances. Within the small limits of error, the lunar and terrestrial isotopic proportions are equal.

Now, let us consider the time of volcanism. Based upon analysis of Rb (rubidium) and Sr (strontium) isotopes in different mineral phases, one can demonstrate that most of the crystalline rocks had their radioactive clocks reset 3.7 billion years ago. The best interpretation of the data is that the rocks were extruded (as a melt) from the lunar interior at that time. Detailed analyses of many rocks shows that there are two major groups as defined by  $\text{Rb}^{87}\text{-Sr}^{87}$  ratios, that the groups do not coincide one for one with the basalt and micro-gabbro classification, and that the rocks do not obviously all have identical ages. A straight-forward interpretation would indicate that the Apollo 11 crystalline rocks may have come from (at least) two

lava flow units of slightly different chemistry and possibly of slightly different age ( $\sim 3.5$ - $3.9$  b.y.). The two rock types would represent, simply, portions of the flows which had different cooling times (deeper = slower cooling - coarser crystallinity).<sup>\*</sup> The reader should be aware that one sample of highly shocked basalt yields an apparent age of  $4.4$  b.y. and is chemically anomalous.

An interesting and significant observation is that the initial ( $\text{Sr}^{87}/\text{Sr}^{86}$ ) ( $\text{Sr}^{86}$  is a non-radiogenic strontium isotope used for normalizing) for the samples is very low but still above that of basaltic achondrite meteorites. It therefore appears that those particular meteorites, for which a lunar origin has been suggested, did not come from the Apollo 11 region. Considering (for one sample!) the lunar rock ( $\text{Sr}^{87}/\text{Sr}^{86}$ ) and the Rb/Sr and modern ( $\text{Sr}^{87}/\text{Sr}^{86}$ ) values for the earth, one can show that the particular rock could not have been in the terrestrial Rb-Sr environment for more than  $\sim 0.3$  b.y. A literal interpretation says that the moon, if it fissioned from the earth, did so prior to  $\sim 4.3$  b.y. ago (this per se won't upset any "fission people" - they usually believe a fission would have occurred shortly after the origin of the earth).

K (potassium) - Ar (argon) ages of the crystalline rocks range from  $2.3$  to  $3.8$  b.y. if one simply correlates total  $\text{Ar}^{40}$  with  $\text{K}^{40}$ . It was thought, before sample analysis began, that the K-Ar ages might be variable on account of argon leakage, with ages thus representing minimum ages. It has been possible, with these samples, to determine that the samples have indeed lost up to  $50\%$  of their argon. When corrections are applied, the "real" ages appear to range from  $3.5$  to  $3.9$  b.y., with clustering around  $3.7$ , consistent with interpretations of the Rb-Sr ages.

Radiometric ages of the crystalline rocks based on the uranium-lead decay schemes yield results ranging from  $\sim 3.8$  to  $4.2$  b.y. The lower values cover the upper range reported for Rb-Sr and K-Ar techniques but the reason for the somewhat greater values for the upper range has not been explained.

A highly unexpected find was the extremely radiogenic nature of lunar lead. Both meteoritic and terrestrial lead are composed of lead isotopes  $\text{Pb}^{204}, \text{Pb}^{206}, \text{Pb}^{207}$ , and  $\text{Pb}^{208}$  with the significant portion of  $\text{Pb}^{204}$  being indicative of "original" lead since it is not produced in any known natural long-lived radioactive disintegration scheme. The lunar lead is almost entirely  $\text{Pb}^{206}, \text{Pb}^{207}$  and  $\text{Pb}^{208}$  indicating that, if the moon came from the same

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<sup>\*</sup>Compare with page 6, top.

pot of chemicals as did the earth and meteorites, it was purged of initial lead before the uranium-thorium clocks were last set. An indication of the large lunar depletion can be seen from the  $U^{238}/Pb^{204}$  of  $>90$  for the moon while the terrestrial value is  $\sim 10$ . ( $U^{238}$  changes very slowly with time on account of its long half-life.)

Let us now turn to the "age" of the regolith. First, it is probable that the regolith represents a composite sample of lunar material which has been built up over an extended period by the meteoroid-induced comminution of "bedrock." Most geologists believe that the source of most of the regolith at Tranquillity must be the  $\sim 3.7$  b.y. old rock presumably underlying the soil there. It is recognized, of course, that at least some, probably minor amount of the material came from distant regions. Evidence for this comes from the one 4.4 b.y. old crystalline rock mentioned before and the determination that several small rock fragments removed from the fines give apparent K-Ar ages of 4.4 b.y. (Caution: There is a large correction for "surface correlated" argon-40 in this calculation.) The surprise enters when one sees that the "age" of the soil, based on uranium-thorium-lead techniques, is 4.6-4.75 b.y. The fact that the uranium and thorium-lead and the lead/lead (less sensitive to uranium, thorium and lead loss or gain) results agree (termed concordant ages) gives confidence to the analyses. Consider also that the "age" of 4.6-4.75 b.y. is what one would predict for the age of the moon or its time of origin. This, combined with the observation that the leads lie on an extension of the meteorite lead evolution curve (meteorites being  $\sim 4.6$  b.y. old) causes one to believe that the old age indeed represents the time of separation of the moon from the general solar system chemical pot. The question remains, of course, how does the soil obtain or keep the signs of the old event? Possibilities include (this is not an inclusive list):

1. Most of the soil was derived from older rocks (4.6-4.75 b.y.) and the  $\sim 3.7$  b.y. rocks are anomalous and represent a sampling quirk.
2. Some "process" acts, in formation of the soil, to "adjust" the ages to their original age. In this sense the soil represents a closed system as regards the whole moon.

Geological reasoning and the preliminary finding that the Apollo 12 samples are  $\sim 1$  b.y. younger than the 11 samples

supports alternative 2 but, then, nobody yet has a good "process." It will take much more analysis of the soil fines and rocks at this and other sites to solve this enigma.

Attempts to date a breccia and bulk soil by the K-Ar method have been thwarted by the abnormally high amounts of argon-40 in the samples (effective ages would be much greater than the apparent lunar age of 4.6-4.75 b.y.). Based upon theoretical physics and upon comparison with argon-36 and -38 in the samples, it is not possible to attribute the argon-40 excess to a solar wind source. A possibility is that the argon-40 is lunar in origin (from the potassium-40 decay), implanted in the surface soil from either a low pressure atmosphere or from higher pressure transient atmospheres created during times of volcanism. A proposed implantation mechanism involves collisions with solar wind particles.

I have already noted the evidence for an impact origin of the fines and breccias. Of interest is the time scale for generation, i.e., rates of erosion. The simplest estimate comes from dividing the mean thickness of the regolith ( $\sim 4\text{m}$ ) by the age of the presumed initial surface on which it formed ( $\sim 3.7$  b.y.), yielding  $\sim 1\text{mm/million years}$ . A more direct analysis, using data on radiation tracks, indicated  $\sim 10\text{mm/million years}$  for a specific rock.

The spread in cosmic ray exposure ages as determined by the usual methods (comparison of the concentration of a radioactive element to that of a non-radioactive element, both of which are produced by cosmic ray bombardment) ranges from  $\sim 10$  to 550 m.y. with possible clustering at  $\sim 100$  and  $\sim 350$  m.y. This indicates that these rocks have been brought to the surface (or near-surface) from depths below 1 to 2 meters (below which they don't "see" cosmic rays) at a reasonably constant rate and that the upper few meters are being mixed or gardened on a 500 m.y. scale. This spread in ages is much greater than the 10 to 30 m.y. mean predicted for the returned rocks based upon actual rock crater statistics and lab-derived erosion criteria. The discussion below may explain the discrepancy.

An interesting extension of the cosmic ray dating technique has been possible from analysis of the (etched) radiation damage tracks produced by cosmic rays in the outer skin (few hundred  $\mu\text{m}$ ) of the samples (this "skin" is ablated from meteorites during earth entry). One group of tracks has

been attributed to galactic cosmic ray iron-group nuclei while new classes have origins tentatively attributed to, solar flare cosmic rays, spallation recoil nuclei (induced by solar flare proton bombardment) and heavy mass ( $\sim 200$ amu) solar wind particles. Only a few fission tracks were observed. Analysis of the iron-group tracks leads to calculated cosmic ray exposure ages much younger than those obtained by analysis of the spallation produced nuclides. For example, one rock gives  $\sim 100$  m.y. by spallation analysis but  $\sim 10$  m.y. by track analysis. Knowing the relative depth dependence of the two methods, the straightforward interpretation is that the rock was in the upper 15-200cm for  $\sim 100$  m.y. but within 15cm or on the actual surface for  $\sim 10$  m.y. (it is not obvious that the 10 m.y. had to be continuous). Three other rocks dated by this technique gave ages of  $\sim 14$ ,  $\sim 13$ , and  $\sim 28$  m.y. consistent with the 10-30 m.y. mean calculated using the crater statistics and lab-derived erosion criteria. Another bit of information to be gleaned from the near surface track analysis is the energy spectrum of the solar flare cosmic rays. The preliminary result is that the flux is proportional to  $E^{-3}$ .

The analysis of radionuclides can be used to yield information on the constancy (or lack thereof) of the cosmic ray flux by comparing measured amounts of long-lived species (half-lives to  $\sim 10^6$  years) with that calculated assuming the current (known) flux. The result indicates relative constancy of solar flare protons and alphas for the last  $10^5$ - $10^6$  years. Of passing interest, the analysis of short-lived radionuclides (half-life  $\sim 1/4$  - 2 yrs) indicates that much of that activity can be ascribed to recent known solar flare events. Of particular interest was the analysis for tritium ( $H^3$ ). Some was expected on account of cosmic ray interactions with lunar material, but there have been recent data to suggest a tritium component in the solar wind. Results thus far are inconclusive regarding such a component in the samples.

#### Solar Wind

The fines of the regolith samples (to  $\sim 10$ cm depth) have proven to be saturated with respect to trapped light solar wind noble gases (present gain = present loss) including H, He, Ne and maybe Ar (the surface concentration of He can be accounted for by  $\sim 300$  years of solar wind impingement). This is a result of the long average exposure of soil to the direct solar wind flux as determined by its cosmic ray exposure age ( $\sim 500$  m.y.)

and the fact that the low energy solar wind particles are trapped in a very thin outer layer,  $\sim 0.2\mu\text{m}$ , of the particles. This latter fact has been established by noting a direct anticorrelation of grain size with gas content and by etching experiments.

The fact that particles are saturated with solar wind gases makes it difficult to determine real solar abundances whether absolute or relative. For example,  $\text{H/He}$ ,  $\text{H/N}$ ,  $\text{He}^4/\text{Ar}^{36}$ , and  $\text{Ne}^{20}/\text{Ar}^{36}$  indicate that the lighter elements have preferentially escaped. One comes to this conclusion by comparing with expected abundances, by noting a systematic decrease in apparent loss with increasing mass, and by comparing abundances between silicate and metal phases of the samples (metals hold the gases more tightly). Evidence regarding relative loss of Ar, Kr, and Xe is contradictory, with some authors believing the heavy gases (Kr and Xe) have undergone significant loss and others seeing no loss.

Despite elemental and possible isotopic fractionations one can "home-in" on solar abundances of noble gases. In all cases it is first necessary to correct for spallogenic components. When such is done, one finds, for example, that  $\text{H/He}$  of  $\sim 8$  is much lower than the expected value of  $\sim 17$  but that  $\text{He}^4/\text{He}^3$  of  $\sim 2800$  is close to that anticipated for solar wind. The  $\text{Ne}^{20}/\text{Ne}^{22}$  values of  $\sim 11-14$  are higher than the earth's atmospheric ratio which may reflect preferential terrestrial gravitational loss of  $\text{Ne}^{20}$  if their initial ratios were the same. That they may have been the same is supported by the identity of the lunar and terrestrial  $\text{Ar}^{36}/\text{Ar}^{38}$  of  $\sim 5$ .

Most of the Kr and Xe is attributed to a solar wind origin. "Anomalies" in krypton and xenon isotopes (relative to certain meteorites) are thought to be caused by differences in the amount of fissionogenic and spallogenic components although the large excess of  $\text{Xe}^{131}$  and somewhat low  $\text{Kr}^{86}$  in many samples are not yet satisfactorily explained. A much hoped for excess of  $\text{Xe}^{129}$  which might be attributable to the short-lived  $\text{I}^{129}$  and lead to calculations of the time of separation of the moon from the solar nebula was not found.

#### Paleomagnetism

A detailed search for remnant magnetism was made on the crystalline rocks and breccias. Determination of the Curie

point ( $\sim 700^\circ$  to  $800^\circ\text{C}$ ) for the magnetic material indicates that the source of magnetism is in iron and ilmenite. Consistent with this, the breccias exhibit more magnetic response than the crystalline rocks, possibly because of a significant addition of iron meteorite material to the breccias. Several investigators find that the rocks do exhibit a remnant magnetism indicative of the presence of a magnetic field at the time the rocks were formed. In the case of the crystalline rocks, the magnetism was presumably acquired as the rocks cooled through the Curie points  $\sim 3.7$  billion years ago. The estimated strength of the field was  $\sim 1500\text{--}2500\gamma$ . If it was a lunar field, it is possible that a small fluid core existed at that time. On the other hand, one cannot dismiss out-of-hand the possibility that the moon was much closer to the earth at that time and was simply "seeing" the terrestrial field (much as it does now as it passes through the geomagnetic tail of the earth) or, less likely, that a much stronger solar wind field existed. Interpretation of the breccia magnetism is harder in that one is not certain of the effect of shock.

A search for magnetic monopoles was completely unsuccessful.

#### Physical Properties

Analysis of the core tube material indicated a bulk density of 1.6 to 1.7 g/cc. Since there are no signs of significant compaction or expansion of the soil, this is apparently close to the real lunar density. Combined with an estimated specific density of 3.1 g/cc, one arrives at a soil porosity of  $\sim 45\text{--}50\%$ . A determination of the apparent (bulk) dielectric of the soil at that porosity gives  $\sim 2.8$  - just what the earth-based radar and Explorer 35 results previously indicated. Tests of radio wave propagation through this material (at 450Mhz) indicate a mean absorption depth of  $\sim 10\lambda$ .

Most of the crystalline rocks have intrinsic densities in the range 3.2-3.4 g/cc (corrected for 0-15% porosity). If the rocks are put into a "squeezing" apparatus and tested for compressibility and sound velocity, it is seen that, unlike most terrestrial rocks, there is a rapid increase as one goes from 0 to 2Kb with a much slower increase thereafter. This pattern is attributed to extensive microfracturing between mineral grains. The P-wave velocity determined at 0Kb is  $\sim 2.6$  to  $2.8\text{km/sec}$  which is consistent with the tentative velocity determinations derived seismically on the moon from the LM ascent stage impact experiment on Apollo 12. The P-wave velocity of  $\sim 5.5\text{km/sec}$  at 2Kb suggests that an efficient wave-guide may exist in the upper several 10's of km of the lunar surface - future lunar seismic experiments should shed light on this possibility. Also significant in the velocity propagation experiment is the finding

that the  $Q$  is very low ( $\sim 10$ ) below 200 bars, a property again attributed to microfracturing in the rocks. As expected, the compressibility of the fines and breccia is much greater than that of the rocks.

The soil, as mentioned above, has obviously been derived from a variety of sources and the particle size distribution reflects various comminution, fusion, aggregation, and disaggregation processes. In toto, however, the processes have created fines with a mean particle diameter around  $40\text{--}60\mu\text{m}$  but a mode closer to  $20\mu\text{m}$  (35 to 50%  $<20\mu\text{m}$ ). Photometric and polarimetric properties of the fines appear to be about the same on lab size specimens as on the 15-20km scale investigated using telescopes. The only anomaly reported is an albedo of 0.09, somewhat darker than the average around Tranquillity as seen from earth.

The generally low albedo of the soil has been attributed by some to the relatively high iron and titanium content of the glass. The reason for the apparent darkening of lunar soil as it "ages", however, has not been convincingly determined. One hypothesis proffered was that devitrification (crystallization) of the glass with time leads to darkening while another attributed it to sputtering which selectively coats particles with metal atoms. Tests for such surface coatings have not been conclusive.

Spectral reflectivity measurements show structure in the 1 and  $2\mu\text{m}$  region attributable to the ferrous ( $\text{Fe}^{++}$ ) iron and (weaker) structure at  $\sim 0.5$  and  $1.3\mu\text{m}$  attributable to titanium in the samples (most of the response is from the clinopyroxene). The strongest "signals" come from rock and rock fragments but diagnostic signals are still obtainable on the fines. The signature from the fines matches that obtained from earth-based work indicating reasonable homogeneity around the Tranquillity site (at least to  $\sim 10\text{km}$  away) but, more important, confirming the previously tentative conclusion that the signature can be interpreted in terms of composition.

Studies of the natural thermoluminescence of the soil shows two major features. First, it is extremely weak, and second, what there is of it appears to increase slightly with depth (core-tube sample). A proposed and reasonable correlation of the increase has been made with the thermal wave propagation, the idea being that the warmer upper layers have undergone more thermal annealing.\* Laboratory tests show that it is the plagioclase feldspar of the samples that is responsible for most of the luminescence and that the luminescence is caused mostly by proton bombardment rather than UV. Measurement

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\*This is consistent with thermal inertia data on returned sample.

of energy conversion efficiencies of  $\sim 10^{-6}$  make it impossible to believe that reported earth-based sightings of lunar liminescence were real.

#### Life-Forms and Organic Chemistry

A thorough search for particles with morphologies which might be indicative of life-forms gave 100% negative results. Consistent with this are conclusions based upon analyses of carbon and carbon-containing compounds.

There is carbon in the samples, with more in the fines ( $\sim 150$  to  $250$  ppm) than in the crystalline rocks ( $\sim 70$  ppm) and in the fines themselves, the carbon is concentrated in the smallest size fractions. In the analyses, most (80-90%) of the carbon comes off as CO with the remainder being primarily  $\text{CO}_2$ . Traces of  $\text{CH}_4$ , HCN, and  $\text{C}_2\text{H}_2$  account for  $\sim 1$  ppm. It is surmised that in the soil the carbon exists in the form of CO in vesicles in glass particles, C as graphite or diamond, metal carbides ( $\text{Fe}_3\text{C}$  has been identified and is a rather common mineral in meteorites), and  $\text{CH}_4$ . The ultimate source of the carbon is probably a combination of indigenous lunar (as represented by the carbon in the crystalline rocks), meteorite, and solar wind. One suspects, but can't prove, that the meteorite contribution is dominant.

The search for organic compounds was particularly frustrating with estimates of upper limits of  $\text{C}_{12}$ - $\text{C}_{36}$  compounds (alkanes and other relatively non-polar compounds) ranging from 0.02 to 5 ppb. Analyses for amino acids gave results ranging from  $\sim 0.01$  ppb to reports of traces at the  $\sim 1$  ppb level. No confidence was expressed that the traces could be attributed to anything but contamination (along lines of contamination, traces of LM combustion products were reported). Traces ( $\sim 0.1$  ppb) of porphyrins (organic pigments essential to life processes) were found but the same traces were detectable in LM exhaust products collected during a test LM engine firing at White Sands. An interesting speculation arising from these observations and pertinent to the "origin" of life is the possible high temperature creation of such organics from simple inorganic source material.

#### The Future

This memorandum represents my attempt to integrate the results of the Apollo 11 sample analyses as reported in

~140 papers at the Apollo 11 Lunar Science Conference in Houston, January 5-8, 1970. It should be clear to the reader that, while problems remain in interpretation of certain results, the data pertaining to geology, mineralogy, petrology, inorganic and organic chemistry, radiogenic isotopes, solar wind and cosmic ray spallation products, magnetic and electrical properties, physical properties, impact metamorphism, and micropaleontology add up to the greatest single advance in the understanding of a planetary-sized body ever attained.

Clarification and extension of the work reported on here will require much more analysis of Apollo 11 samples and of new samples from Apollo 12 and future sites. If we are to effectively utilize future lunar missions as regards site selection, instrument emplacement, sampling techniques, geologic observations, and orbital sensing, we must comprehend and continually up-date the summation of all the lunar investigations. To that end, readers are encouraged to inform the author of critical omissions, possible mis-interpretations and new data.

*NW Hinners*

N. W. Hinners

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